The Dark Shadows of the Jolly Green Giants: Urgent Policy and Research Priorities in Renewable Energy Technologies

Keith R. Skene

Abstract

This article reviews the environmental, ecological, and social impacts of current renewable energy technologies. Problems of these technologies are highlighted in terms of manufacturing, installation, lifetime, and end-of-life. What emerges are concerning issues that need to be urgently addressed as they potentially threaten the recovery of the Earth system and therefore also impact society. It is suggested that many of these issues have been overlooked because of our focus on carbon reduction, which, while important, may lead to a failure to deal with other equally concerning threats, and even exacerbate them. These threats are highlighted and then urgent priorities, in terms of policy, regulation, and research, are identified, paving the way to an energy future that does not threaten the functionality of the Earth system. Finally, key underlying themes are identified that may inform our decision-making as we move forward. If we are to aim for a truly sustainable future, in terms of economics, ecology, and society, this article argues that we must seek to aim higher than current practice and plan for a future that not only arrests anthropogenic climate destabilization and its threat to many species, including our own, but that builds the foundations for ecological recovery. Better-than-before is not good enough. We need energy technologies that minimize our impact on our planet.

Keywords: biofuels; electric vehicles; hydropower; marine renewable energy; photovoltaics; wind energy

Introduction

Currently, 81 percent of total primary energy supply and 66 percent of electricity generation are derived from fossil fuels, with renewable energy contributing 25.6 percent and nuclear energy representing 10.6 percent (International Energy Agency, 2018). It is expected that 84 percent of global energy requirements will be met through fossil fuels by 2030 due to increasing energy demands (Bhagea et al., 2019). The combustion of fossil fuels is by far the largest human source of global greenhouse gas emissions, releasing more than 30 billion tonnes of carbon dioxide (CO_2) into the atmosphere each year (Intergovernmental Panel on Climate Change, 2014).

It is important to recognize that the climate issues do not all revolve solely around CO_2. Using the greenhouse warming potential (GWP), which compares the energy absorption and release of a given gas with that of CO_2, where GWP (CO_2) = 1, methane has a GWP of between 28 and 30, nitrous oxide GWP is between 265 and 298, while fluorocarbons have GWPs thousands of times higher than CO_2.

The issues surrounding fossil fuels do not only relate to climate destabilization. In the United States, in addition to fossil fuel power plants contributing 39 percent of the nation's CO_2 emissions, 67 percent of SO_2 emissions and 41 percent of mercury emissions stem from this same sector (Environmental Protection Agency, 2020). In addition, concerns surround polycyclic aromatic hydrocarbons (PAHs) (a class of hazardous air pollutants that include known carcinogens and neurotoxins), volatile organic chemicals (VOCs) and NO_x (the latter of which leads to ozone production at

Biosphere Research Institute, Scotland, UK.

low altitude levels), which are strong respiratory irritants impacting lung development and function in children (Tzivian, 2011).

Children represent the subgroup of the population most affected by air pollution and will be the primary beneficiaries of policies to reduce fossil fuel emissions over the next two decades (Cifuentes et al., 2001). Fine particulate matter (PM) and cadmium create issues in terms of respiratory and carcinogenic disease. Early-life exposures to PM2.5, PAHs, and O_3 all have a negative impact on fetal development (Choi et al., 2006). Prenatal exposure to PAHs is associated with developmental delay, reduced IQ, and symptoms of anxiety, depression, and inattention (Perera et al., 2012).

As a result of such concerns for the environment, ecology, and human health, there has been an increasing exploration of alternative, renewable energy resources. Many of these technologies have long histories, stretching back over 100 years (Figure 1).

The term *renewable energy* was originally coined as an antonym to exhaustible energy, particularly in terms of fossil fuels (Bell, 1906). There are projections suggesting that the world's reserves of oil and gas will run out around the middle of this century with coal completely depleted 60 years later (Norouzi et al., 2020). Yet many of the natural resources required to manufacture renewable energy technologies, such as copper, graphite, gold, lithium, rare earth metals (REMs), uranium 235, and platinum, are themselves exhaustible. Furthermore, supply chains can be deliberately disrupted during political disputes (Mancheri et al., 2019).

The International Energy Agency (IEA) defines renewable energy as "energy derived from natural processes that are replenished at a faster rate than they are consumed" (IEA, 2018). The U.S. Department of Energy (DOE) utilizes the term *clean energy* (DOE, 2018), which encompasses basically all energy sources other than fossil fuels. Missing in these definitions is any consideration of the environmental damage beyond carbon, the social damage incurred through the mining of the chemicals required for construction of the underpinning technologies, and the end-of-life (EoL) consequences for the Earth system. The renewability of the energy sources, be they wind, water, or sunlight, and the carbon footprint, inadequately cover the deeper issues relating to how we generate our energy.

It has been argued that sustainable energy may be a more useful term. Tester (2005) defined sustainable energy as, "a dynamic harmony between

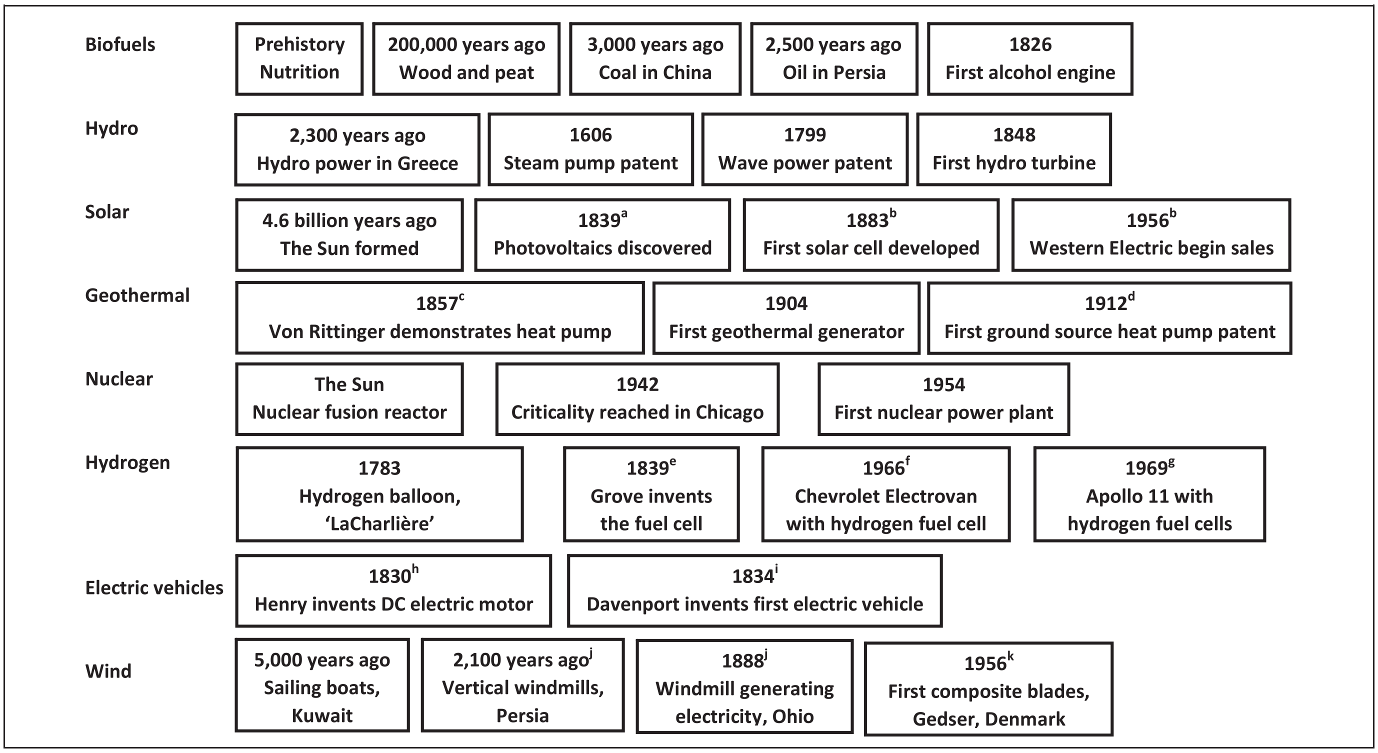

Figure 1. Historical development of current renewable energy technology (Skene and Murray [2017] unless otherwise noted)
[a]Mickey, 1981; [b]Jungbluth et al., 2009; [c]Sanner, 2017; [d]Wirth, 1955; [e]Grove, 1839; [f]GM Heritage, 2019; [g]Williams, 1994; [h]Henry, 1831; [i]Bansal, 2005; [j]Kaldellis & Zafirakis, 2011; [k]Brøndsted et al., 2005.

the equitable availability of energy-intensive goods and services to all people and preservation of the Earth for future generations" (p. 8). A sustainable energy source would be one that is not substantially depleted by continued use and does not involve significant pollutant emissions or other environmental problems, health hazards, or social injustices (Baykara, 2018).

As Harjanne and Korhonen (2019) have suggested, "It would be best to avoid renewable energy as a term altogether and instead to conceptualize energy sources based on their carbon emissions and whether they are based on combustion or not" (p. 337). However, it is an inescapable truth that carbon is not the only threat to humanity. Species diversity, ecosystem functioning, soil stability, social well-being and justice, food chains, and biogeochemical cycling are also critically important.

There is a tendency in the literature to compare renewable energy generation with that of fossil fuels and, undoubtedly, this will always favor renewables. However, in aiming for a truly sustainable future in terms of economics, ecology, and society, this article argues that we must seek to aim higher than this, and plan for a future that not only arrests pollution and its threat to many species, including our own, but that builds the foundations for ecological recovery. Better-than-before is not good enough. We need energy technologies that minimize our impact on our planet.

Fundamental to this is the necessity of understanding the planet as a complex system, where nonlinearity, emergence, component sub-optimality, self-organization, and feedback all play essential roles (Skene, 2018, 2020a). As such, planetary functioning must be prioritized over all else in recognition that the blueprint of recovery lies within the Earth system itself.

The blind pursuit of a low-carbon future funded by green energy technologies also evades the more fundamental issue of using less energy and threatens to result in the green paradox, wherein ill-designed policies and legislation lead to a worsening of environmental damage (Berkhout et al., 2000).

This reviews the environmental and social impacts of current renewable energy technologies. Issues are highlighted in terms of manufacturing, installation, lifetime, and EoL of these technologies. Urgent priorities in policy, regulation, and underpinning research are then suggested that can pave the way for a truly sustainable future. Finally, key underlying themes are identified that may inform our judgment of the best path forward.

Materials and Methods

An extensive literature review, involving over 1,000 research papers, was undertaken, from which were distilled significant issues relating to renewable energy technology in terms of manufacturing, installation, lifetime, and EoL concerns, across environmental and sociological arenas. Policy and research priorities were identified, targeted at addressing these issues, and the results are discussed in terms of future work.

Literature Review of Issues with Current Renewable Energy Technologies

This section is a review of the impacts of the major technologies upon the environment and society in terms of their manufacture, installment, lifetime, and EoL. The findings are summarized in Table 1.

Wind Energy

Wind energy has one of the longest histories as a renewable energy source (Figure 1) and has proven important in transport and industry for thousands of years. More recently it has been utilized to generate electricity. Wind power is viewed as an important path to zero carbon emissions, with 1 GW of offshore wind power avoiding more than 3.5 MT CO_2 (Global Wind Energy Council /Global Wind Organisation [GWEC], 2020). Leahy (2019) reported a global capacity of around 660 GW in 2019. Vance (2009) has claimed that wind energy is so abundant as to allow the provision of power for all of humanity. With the exception of hydropower, wind power is closer to commercial profitability than any of the other renewable sources (Jaber, 2013).

Denmark currently has 48 percent of its power supplied by wind turbines, whereas the United States has a mere 4 percent (Nazir et al., 2019). The British government has committed to powering every house in the United Kingdom through offshore wind power by 2030, requiring 40 gigawatts per year (GWy^{-1}), four times the current levels. The United Kingdom is well situated in terms of available wind energy, and, as early as 2011, the Renewable Energy Roadmap provided by the Department of Energy and Climate Change identified wind energy as a key technology (Department of Energy and Climate Change, 2011).

From representing 1 percent of global wind installations by capacity in 2009, offshore wind grew over 10 percent by 2019. Global Wind Energy Council/Global Wind Organisation (GWEC) Market Intelligence

Table 1. Significant Issues Related to the Construction (C), Lifetime (L), and End-of Life (E) of Renewable Energy Technologies

Technology	Environmental Issues	Human Issues	Ecological Issues	Other Issues
Wind	soil erosion (C), compaction (C), eutrophication (C), atmospheric circulation (L), CF/GF waste (E)	REMs: human toxicity	birds (L), bats (L)	REMs: resource security (C), wind conditions (L)
Hydro	methane (L), CO_2 (L), groundwater salinization (L), coastal erosion (L)	displacement (C), dam failure (L), cultural site destruction (C)	fish migration (L), toxic sediment (L)	susceptible to climate destabilization (L)
Geothermal	high-water use (C), high CO_2 release (L), acidification (L), methane release (L), thermal discharge (L)	mercury, arsenic, H_2S (C, L); seismic activity/eruption (L), groundwater contamination (C)	anoxia (L)	limited distribution (L)
GSHP		groundwater contamination (C), explosions/suffocation/ poisoning from trapped gas layers (C, L)		
Photovoltaics	high energy use (C), organic solvents (E), landfill leaching (E), utility PV transformer oil (L)	carcinogenic Cd (C), toxic leaching (E), silane gas (C), REMs: human toxicity (C)	toxic leachates (E)	REMs: resource security (C), unpredictable sunlight
Electric vehicle	acidification (C); water use (C); CO_2, CO, SO_2 (C, L); high energy use (E)	Cu Al, arsenic (C); REMs: human toxicity (C); cobalt mines (C); dioxins (C)	eutrophication from lignite mining (C), ecotoxicology from steel/copper mines	REMs, cobalt, graphite, lithium all with resource security issues (C); recharging issues, greenwashing (L)
Hydrogen	fossil fuels (C); CO_2, CO, mercury (C); ozone depletion (L); albedo effect (L)		soil microbiology (L)	tequires more energy to produce than is released
Biomass	water use (C), land use (C), air quality (L)	competes with agriculture (C), particulate matter (L)	deforestation (C), eutrophication (C)	seasonality for microalgae (L)
Marine	hydrodynamics (L), sediment transport (L)	REMs: human toxicity (C)	migration paths (L), food chain issues (L), ecocide (C)	ownership issues (C, L), REMs (C)
Nuclear	thermal discharge (L), acidification (E), possible radiation contamination (C, L, E)	radiation risk (C, L, E), nuclear proliferation (L)	radiation risk (C, L, E), uranium mining (C)	

expects that over 30 GW of offshore wind capacity will be added annually by 2030, totaling 205 GW (GWEC, 2020). However, significant environmental and social issues arise in terms of manufacturing and EoL, and, to a lesser extent, during the lifetime of the turbine (see Table 1).

Construction issues: The manufacturing stage is energy intensive and is associated with a range of chemical processes. Perhaps the most significant issue relates to the neodymium (NdFeB) permanent magnets that form a key component of the more modern turbines, allowing generation of electricity even at low wind speeds. Typically, a wind turbine requires 250 to 650 kg of NdFeB magnet to produce 1 MW of electrical power (Yang et al., 2017). These magnets contain the REMs neodymium (Nd), praseodymium (Pr), dysprosium (Dy), and terbium (Tb). China domestically extracts 95 percent of the REMs and has drastically reduced exports in the past. REMs are classed as critical resources and pose resource security risks. REMs are also responsible for significant health impacts in the population surrounding the mines in China (Sun et al., 2017; Zhang et al., 2000), particularly for children (Wu et al., 2019). Furthermore, Horikawa et al. (2006) reported that some 15 to 30 percent of the raw materials are wasted as scraps at NdFeB manufacturing sites during the shaping and finishing.

The second major issue relates to the plastics used in much of the bodywork of the turbine, including the rotors. Carbon fibers are energetically expensive to make. The manufacturing energy consumption of virgin carbon fiber is 286 MJ/kg, which is 4.5 times higher than for glass fiber and 1.2 times higher than for epoxy. The material needed to make the fibers includes propene, derived from oil. Side products include hydrogen cyanide. A 5 MW wind turbine produces more than 50 tonnes of unrecyclable plastic composite waste (Ziegler et al., 2018).

The major in-process wastes are the dry fiber off-cuts, cured composite off-cuts from the blade edge and root, resin residue in the flow mesh and container, and the dust from the polishing process. Defects and testing blades add to manufacturing waste. During onshore installation, soil erosion, with all of its associated issues (including eutrophication of water bodies, increased landslide risks, and habitat disruption) is commonplace. Soil compaction from vehicles greatly impacts the soil (Shen et al., 2017). Offshore installation has the potential to greatly impact marine environments during construction.

Wang et al. (2019) reported that the annual life-cycle greenhouse gas (GHG) emissions from onshore wind turbines are 1,664 t CO_2e with a life-cycle GHG emission intensity of 0.08 kg CO_2e/MJ. The annual life-cycle GHG emissions from offshore wind turbines is 3795 t CO_2e, equating to a life-cycle GHG emission intensity of offshore wind turbine of 0.13 kg CO_2e/MJ. Much of this additional cost is related to the extensive foundations needed for offshore turbines. Therefore, it is important to design better floating platforms for offshore turbines to achieve the equivalent GHG emissions of onshore turbines.

Lifetime issues: A fundamental issue relating to turbine function is the intermittent nature of wind. This creates significant problems in terms of energy security. Difficulties in storing energy may lead to challenges to grid supply continuity.

Offshore turbines present specific issues relating to stability in deeper waters and connectivity to the onshore grid. Current Habitat Regulations Assessments (HRA) require compensatory payments, increasing costs. Operational wind farms impact bird mortality, though relatively little compared to birds killed by cats (Calvert et al., 2013), particularly if the wind farm is located on migratory pathways. A major study has concluded that developments off the east coast of Scotland, approved by the Scottish Government in 2014, could cause the additional mortality of at least 2,000 gannets per year (Cleasby et al., 2015).

Bats can also be impacted, due to lighting around the site. A study from the University of Colorado at Denver concluded that well over 600,000 bats may have been killed at wind energy facilities in 2012 alone (Hayes, 2013). It is possible that as turbines become larger and reach higher, the risk to bats and nocturnally migrating passerines will increase (Jaber, 2013).

Noise generated from wind farms stems from both aerodynamic and mechanical origins. Stand-alone turbines create more of a noise issue than large wind turbine sites (Miller & Keith, 2018). The impact of offshore turbine noise upon marine life is currently unknown. Concerns have been raised that significant increases in the scale of wind turbine use could substantially impact atmospheric circulation and weather systems (Marvel et al., 2013).

EoL issues: The typical operational lifetime of a wind farm in Spain is over 20 years, whereas in Germany it is around 16 years. While lifetime extension or relocation represent the most environmentally robust methods of dealing with EoL issues, these strategies merely push the problem further down the road. Wind farm operators may decide to end the actual operational life earlier due to the development of more advanced technologies that return greater profitability (Leahy, 2019).

Turbine bodywork represents a significant challenge in terms of recycling. It is estimated that composite materials from blades worldwide will amount to 330,000 tonnes of waste per year by 2028, and to 418,000 tonnes per year by 2040 (Ramirez-Tejeda et al., 2017). By 2050, other loses in manufacture, transport, and operation, such as severe weather damage, has been estimated to total 0.8Mt each year (Liu & Barlow, 2017).

Blades are made of glass fiber reinforced plastic (GFRP) and carbon fiber reinforced plastic (CFRP). These plastics are lightweight but have high strength, durability, rigidity, tensile strength, chemical resistance, and temperature tolerance, and low thermal expansion. All of these characteristics provide challenges for recycling. Limited use in urban play structures, street furniture, and signage (Jensen & Skelton, 2018) only postpone the inevitable waste issues and have an insignificant market potential relative to the scale of the waste.

Composite blades are, by their very nature, a combination of different materials, which represent a further challenge in terms of separation and varying chemistry. At the global scale, the cumulative total blade waste is expected to reach 2.9 Mt per year by 2050 (Liu & Barlow, 2017) and turbine blades are increasing in size as development continues.

GFRP, currently the most common material in rotor blades, recycles poorly, whereas CFRP can be more easily recycled into higher quality materials/products (Ginder & Ozcam, 2019). Reuse of GFRP in concrete is energy intensive due to the cost of grinding. Shredding represents significant down-cycling. Furthermore, secondary markets for recycled fibers are insignificant.

The net impacts of mechanical recycling, incineration (resulting in significant amounts of ash that requires disposal), chemical recycling, and high voltage fragmentation are between 86 and 95 percent of the net impact of landfill (Lui & Barlow, 2017), meaning that there is little potential for significant environmental impact reduction from using these processes. In addition, incineration involves air pollution, releasing volatile and semi-volatile organic compounds and polycyclic aromatic hydrocarbons, many of which are highly toxic (Lemieux et al., 2004). At the heart of the issue lies the conflict between larger, longer-lasting, reliable, and therefore more efficient blades, and increasing challenges in EoL scenarios.

During the iron removal process in recycling the NdFeB magnets, some 20–30 percent of REMs present in the leach solution are lost due to coprecipitation (Rabatho et al., 2013). Furthermore, the process is energy-intensive, requiring temperatures of over 1,100 K for roasting, and the consumption of high amounts of acid/alkali. Furthermore, such pyrometallurgical methods produce impure REMs.

Climate destabilization threats to wind power include predicted increases in lightning strikes, increases in cyclone and hurricane intensity, and, in the case of offshore turbines, sea ice and storm surges (D. Zhang et al., 2019).

Hydropower

Hydropower involves the direct use of water flow for the production of renewable power. The percentage of US electricity generated by hydropower is only 7 percent of total production. Some 40,000 large dams, most of which were built in the past 50 years, now obstruct the world's rivers. The world's largest impoundment, the 8,500 km^2 Volta Reservoir behind Ghana's Akasombo Dam, flooded 4 percent of that nation's land area. The largest hydroelectric power plant in the world is the Three Gorges Dam in China, with an electricity production capacity of 22.5 GW.

Construction issues: If vegetation existed in the previously unflooded areas behind a dam, which is usually the case, CO_2 and CH_4 are released from anaerobic degradation of this organic material (Førsund, 2015). The weight of water behind the dam can impact the geological stability of the surrounding landscape, with potentially disastrous consequences, such as in the Vajont Dam in Italy. The manufacture of concrete and steel, used in construction, release large amounts of carbon dioxide. The construction of dams can alter surface and groundwater flows significantly.

Lifetime issues: Sediment trapped behind the dam can become toxic due to anaerobic processes. Changes occur in heat and pollutant fluxes, while the dam itself often prevents fish migration (Edenhofer et al., 2011). Downstream decreases in water and sediment levels have widespread consequences in terms of delta formation at the mouth of the river, increased coastal erosion, and increases in salinity in estuaries, resulting in salinization of groundwater (Rashad & Ismail, 2000).

Large hydroelectric dams have significant direct impacts on society. Many people are forced to relocate. In the case of the Aswan dam, over 100,000 people were displaced, while the Three Gorges project led to the displacement of 1.3 million people and the destruction of many structures of cultural significance, in addition to vast areas of farmland (Jackson & Sleigh, 2000). Longitudinal research by Wilmsen and Van Hulten (2017) has indicated that rural households relocated to new farming land fared better than rural households moved to urban areas. Since culture is intertwined with landscape in rural areas, the complete eradication of this landscape devastates such cultures.

Failure of dam structures has led to many deaths, and with climate destabilization leading to increases in rainfall intensity, such failures are likely to increase (Lettenmaier & Gan, 1990). Other locations will experience significant reductions in rainfall, threatening the electricity production capacity of a given dam, exacerbated by increased competition for water between irrigation and power (Raje & Mujumdar, 2010). Control of waterways can also be a politically sensitive security issue (Roussi, 2019).

Geothermal

Geothermal energy allows production of hot water, heating, and electricity. It originates from radioactive decay of minerals, including uranium, thorium, and potassium. Some 47 percent of the total global energy demand is used for heating or cooling (Giambastiani et al., 2014). If only 1 percent of the total estimated available geothermal energy were utilized by humanity, it could provide 2,800 years of power at a constant rate (Olasolo et al., 2016). Thus, geothermal energy has the potential to play a very significant role and represents a reliable, continuous energy supply, unlike wind, tidal, or solar energy (Paulillo et al., 2019). Other benefits include lower water use than many forms of energy generation and lower land requirements (404m^2/GWh of land space, much lower than wind, with 1335m^2/GWh) (Wong & Tan, 2015).

Unfortunately, this source of energy is highly dependent on local geology. Geothermal plants are concentrated in tectonically active countries such as Iceland, Italy, and New Zealand. In Iceland, almost 99 percent of houses and buildings are heated by natural hot water. In 2015, geothermal energy produced less than 0.5 percent of global electricity (Bertani, 2016). However, the total capacity was expected to almost double, to 21 gigawatt electricity (GWe), between 2015 and 2020. Another issue relates to the fact that geothermal heat cannot be distributed easily over long distances.

Granites contain small quantities of radioactive potassium, thorium, and uranium that decay over periods of billions of years, and in doing so produce heat. These rocks are much more widespread globally. It has been estimated that even in a relatively tectonically inactive nation such as the United Kingdom, in combination with deep sedimentary basins and flooded mines, geothermal energy could produce between 1 and 10 GW ($\sim$30% of national electricity generation) (Gluyas et al., 2018).

Construction issues: Roughly 80 percent of the lifetime environmental impacts occur during exploration and construction phases, including acidification, eutrophication, human toxicity, respiratory inorganics, photochemical ozone formation, and resource depletion, mostly from diesel for drilling, steel production for well casings, copper for piping, cement, plastics, titanium, and drilling waste. Dust, noise, and high levels of water use (up to $30\,\text{m}^2$ H_2O per m depth drilled) also create issues (Clark et al., 2011). The process of drilling experimental boreholes, often in fragile ecosystems, leads to soil erosion, geological activity, and contamination of groundwater from surface water. The amount of arsenic in the Waikato River has more than doubled since the installation of the Wairakei power plant in the late 1950s (Shortall et al., 2015). Construction risks also include landslides, subsidence, and soil compaction.

Lifetime issues: Hydrogen sulfide, mercury, arsenic, and other chemicals are released into the atmosphere from geothermal plants. While geothermal energy generally emits relatively low levels of CO_2, an environmental impact assessment of four geothermal power plants located in Italy concluded that greenhouse gasses emitted from the plants rivaled natural gas plants, approaching 700 gCO_2-e/kWh (Bravi & Basosi, 2014). Here, the likelihood of acidification was 2.2 times higher in the geothermal power plants than coal power plants and 28 times higher than natural gas power plants.

Other issues relate to long payback time, high initial capital costs, difficulty in accessing the resource, and difficulty in modularization (Li et al., 2015). During their lifetimes, geothermal power plants are often faced with the issue of silica scaling, which significantly increases the cost of maintenance. In addition, the dangers of hydrothermal eruption (Shortall et al., 2015) and seismic activity (Gischig et al., 2014) pose concerns in tectonically active sites. Work by Gischig et al. (2014) showed that deep geothermal energy plants are best situated in remote areas, far from housing, to reduce the threat of seismic activity on human populations, hence increasing acceptance.

The release of acidic or alkaline effluents can contain chlorides and sulfides or toxic elements, such as aluminum, boron, cadmium, lead, mercury and fluorine (Wetang'ula, 2004). Geothermal power plants are extremely inefficient and discharge large amounts of waste heat into the atmosphere, lakes, and natural water bodies, which can impact ecology, local cloud formation, and local weather patterns (Kristmannsdóttir & Armannsson, 2003).

Due to increased heat and acidity, the area around the Wairakei geothermal development in New Zealand has witnessed more invasive and nonnative species, threatening endemic species, thus impacting resilience and community stability (Shortall et al., 2015). Impacts on tourism can also occur. For example, in New Zealand, the development of geothermal energy has caused irretrievable extinction of more than 100 geysers (Barrick, 2007). In terms of operation, methane production contributes to climate change while also impacting ozone production. Maintenance involves additional use of copper, leading to ecotoxicology and human toxicity.

Open loop systems, such as dry steam or flash steam cycles, release gases normally trapped underground. Binary cycles, which are closed-loop systems, offer a potentially better option with regards to this issue (Bravi & Basori, 2014).

EoL issues: EoL costs are particularly focused on freshwater toxicity relating to copper in the wiring.

Ground Source Heat Pumps (GSHP)

The heating and cooling of buildings account for about 40 percent of the world's total energy demand (Nejat et al., 2015). Ground source heat pumps (GSHPs) offer a potentially useful solution, utilizing near-surface temperature differences to heat or cool edifices. GSHPs are grouped into two main categories: air-source and ground-source. Less common types utilize low-grade waste heat, surface water, or solar heat as heat sources. Closed-loop systems circulate a heat carrier fluid within a closed pipe system, whereas open systems exchange heat with the groundwater which is usually re-injected into the aquifer.

Construction issues: Construction of a GSHP system involves mining, production, construction, transportation, and drilling. These processes lead to a range of issues including air pollution, groundwater contamination, acidification, and eutrophication.

Lifetime issues: GSHP systems can have serious impacts on the structural integrity of buildings. The most well-documented example occurred in Staufen (Germany) due to the transformation of anhydrite into gypsum (Sass & Burbaum, 2010). This caused a differential ground uplift, which resulted in serious damage to historical buildings in the town center.

The drilling of borehole heat exchangers (BHEs) is considered a possible trigger for cross-contamination between aquifers. Local-scale subsidence due to salt layer dissolution has also been reported (Fleuchaus & Blum, 2017). Relatively shallow gas layers, containing CH_4 or hydrogen sulphide (H_2S), can be intercepted by wells or BHE drilling (Sachs & Eberhard, 2010), with the potential risks of explosion, suffocation, or poisoning. BHE installation poses risks of antifreeze release from pipe leakage.

Another major concern involves physiochemical alterations of groundwater due to temperature changes induced by the operation of GSHPs relating to underground thermal energy storage (Fleuchaus et al., 2018).

Photovoltaics (PV)

As has been noted, energy acquired directly from the sun not only underpins our food supplies, but provides many of our sources of energy, including fossil fuels, biofuels, wind energy, and hydropower. However, the exploitation of solar power through photovoltaics (PVs) is the most direct technology. The first solar cell was developed as early as 1888, but solar modules would not enter the commercial market until 1956 (Figure 1). By the end of 2019, PVs accounted for 627 GW output (International Energy Agency, 2020).

Currently, the most common PV module uses crystalline silicon technology, followed by cadmium telluride (CdTe) thin-layer modules. The former has the advantage of high efficiency while the latter are more flexible and cost-effective (Nain & Kumar, 2020). Crystalline silicon modules release fewer materials into the environment compared to thin-film modules.

PVs are commonly utilized in two ways: distributed PVs (residential), which consist of a small number of modules, usually placed on the roof of a residential property; and utility PVs, which occupy land areas as large as 650 hectares. The Solar Energy Generating Systems (SEGS) in California are, together, capable of powering 200,000 homes.

Construction issues: Vellini et al. (2017) emphasized that recycling is essential if PV technology really is to represent a sustainable energy option, both at the social and environmental levels, but there are also significant issues related to the manufacturing of PV modules (Table 1). Silicon crystal PV module production involves the release of silane gas, silicon tetrachloride, and chlorosilane gas. Another problem is the release of silica dust during mining. The high temperature needed for crystalline-silicon production makes it an energy-intensive and expensive process. Furthermore, some 80 percent of the initial metallurgical-grade silicon is lost during the mining process (Lamnatou & Chemisana, 2017).

CdTe PV module production requires much less energy than silicon-crystal PV production. Because of this, all environmental impacts of CdTe module production associated with the use of fossil fuels are significantly lower than those related to the silicon module production (Vellini et al., 2017). However, CdTe module production involves the release of Cd, a significant carcinogen, at levels only slightly lower than fossil fuels (around 0.26g/GWh for CdTe panels, compared to 0.3g/GWh for natural gas (Lamnatou & Chemisana, 2017)). There is no release of Cd during the operational phase, but concerns returnatEoL.

There are resource security issues surrounding tellurium and its scarcity may be a bottleneck for the production of CdTe cells. The estimated average crust abundance is 3 ppb and its distribution is extremely heterogeneous (X. Zhang et al., 202019).

Lifetime issues: There is significant transformer oil waste in the maintenance of utility PVs. Utility PVs require large areas of land and therefore may displace forest, grassland, or agricultural land. While there is an issue in terms of ecological damage, deforestation to make space for these large utility PVs causes net CO_2 emissions of, at worst, 86 g CO_2 kWh^{-1}, much less than coal (1,100 g CO_2 kWh^{-1} (Turney & Fthenakis, 2011).

EoL issues: PV module recycling is not an easy task because the units are assembled from multiple, extremely different materials (Latunussa et al., 2016) and often in small quantities. Component separation involves organic solvent pollution while silicon recycling leads to organic liquid waste. Indeed, the environmental benefits caused by raw materials recovery during the recycling process are quite small due to the energy-intensive processes required (Bogacka et al., 2017). It is estimated that cumulative PV capacity could increase up to 4,500 GW by the end of 2050. The associated PV waste would be increased to a value of 70 to 80 million tonnes (International Renewable Energy Agency, 2016). Thus, EoL considerations are paramount.

Recycling REMs is problematic because of difficulties in separation and complex chemistry. While these REMs account for only 1 percent of the module volume, their value is significant (Xu et al., 2018). Silver is also being lost.

Given the issues surrounding recycling, the bulk of panels end up in landfill, where leaching is a serious issue. In low-pH conditions, more than 15 percent of the lead content can be released from crystalline silicon PVs in 56 days (Zapf-Gottwick et al., 2015). Ramos-Ruiz et al. (2017) reported that 73 percent of Cd and 21 percent of Te were released in a simulation of acidic landfill conditions. Molybdenum is another problematic leachate.

Distributed PVs are problematic in terms of individual owners not knowing what to do with EoL panels. Given that the working life of a solar panel is approximately 25 to 30 years (Nain & Kumar, 2020), the original purchaser may have moved house when EoL decisions need to be made.

Passive Solar heating and cooling Passive solar heating and cooling, wherein architectural components such as facades, solar chimneys, or roofs are utilized to cool or heat buildings, avert all of the supply chain and end-of-life issues identified for active solar heating and cooling (Chan et al., 2010; Hastings, 2020). Many such nonmechanical approaches can be found in nature and in pre-industrial architecture. Such structural solutions do not require power to run them, and should be examined in terms of energy efficiency and social justice, particularly relating to social housing, where they can help avoid fuel poverty.

Electric Vehicles (EVs)

Oil products currently account for about 90 percent of total transportation fuel. Yet electric vehicles (EVs) initially dominated transport propulsion (Figure 1), with internal combustion engines only overtaking them by around 1910 (Bansal, 2005). Transportation now accounts for 23 percent of the world's CO_2 emissions (International Energy Agency, 2014). In the EU, 500,000 premature deaths every year are due to pollutants, where transportation represents the main air pollutant source, particularly in urban areas (Valverde et al., 2018).

With increasing concerns over climate destabilization, the 2015 Paris Agreement set a target for a global plug-in EV stock of 100 million vehicles by 2030 (United Nations Climate Change, 2015). One of the major impediments to reducing the cost of EVs remains the cost of their batteries, which can make up about 50 percent of vehicle production costs but only lasts for 10 years. The issues surrounding EVs relate mainly to supply chain integrity, battery issues, and the sources of recharging electricity.

Construction issues: In a comparison between hydrogen, methanol, and EVs, EVs were found to be most damaging in terms of human toxicology (mostly from copper and aluminum refining and battery disposal), eutrophication (lignite mining spoil), and terrestrial ecotoxicology (steel and copper production) (Bicer & Dincer, 2017). Lithium-ion batteries are currently the sole battery technology used in modern EVs due to their high specific energy and power densities compared to alternative battery types.

Of the range of lithium batteries, Azevedo et al. (2018) reported that nickel-cobalt-manganese (NCM) batteries represent the largest cathode market share in EVs globally, accounting for 57 percent of vehicles sold in 2017. Lithium-iron-phosphate (LFP) batteries comprise 24 percent of the market, nickel-cobalt-aluminium (NCA) 16 percent, and lithium-manganese-oxide (LMO) batteries account for 4 percent (Pontes, 2019).

While LFP and LMO battery chemistries utilize no cobalt and low amounts of lithium and graphite compared to other technologies, in recent times the market share of these battery types has decreased because they weigh more. There exists some 25 million tons of lithium in addition to another 5 million tonnes in marginal stocks (Skene & Murray, 2017). If all the cars in the world (around 1 billion) contained a lithium battery, this would require the extraction of 4 million tonnes of lithium every 10 years. It is predicted that lithium will begin to experience a supply shortage in the commodity market after 2023 (Choubey et al., 2016). Lithium production will need to be increased at rates unparalleled in recent history in order for electric vehicle demand to maintain a sustainable market share (Ballinger et al., 2019). EV demand is forecast to require nearly all of the global lithium produced in 2030 even if supply increases at historic rates.

To secure sufficient lithium, it is likely that a more environmentally damaging ore, spodumene (a silicate of lithium and aluminum) could be utilized, which requires a considerable amount of process energy (Ebensperger et al., 2005). Sea water and pegmatite rock promise significant new resources of lithium (Narins, 2017), but extraction requires large amounts of energy. Notter et al. (2010) claim that lithium extraction amounts to only 2.3 percent of the environmental impact. However, these results are valid only providing lithium carbonate (Li_2CO_3) is produced from brines.

Australia, Argentina, and Chile together account for 91 percent of global lithium production. The lithium market has a Herfindahl-Hirschman Index (HHI) value of 3,090 (HHIs greater than 2,500 indicate an elevated supply risk). Human health damage accounts for 43 percent of the complete environmental burden caused by the production of a lithium-ion battery (Notter et al., 2010). Brine-sourced lithium creates significant social issues, leading to concerns relating to water pollution among indigenous peoples, who generally occupy the areas around the mines, which are situated in some of the most pristine high-altitude (essential for crystallization of Li_2CO_3) regions on the planet, with extremely vulnerable ecosystems. W. Liu et al. (2019) identified lithium mining activities as one of the major stressors leading to local environmental degradation.

Permanent magnet motors, which are reliant on the REMs neodymium, praseodymium, dysprosium, and terbium, are the dominant technology for EVs as they are for wind turbines. They are used in 100 percent of plug-in hybrid vehicles (PHEVs) and at least 62 percent of battery electric vehicles (BEVs), equating to some 75 percent of all EVs. As already noted, the extraction of these metals has devastating impacts on children living near mining areas.

Graphite, while not contributing to greenhouse gas emissions (the carbon remains in the battery), has a distinctly higher cumulative energy demand, as it mostly comes from hard coal coke. This also means that mining of coal continues to be necessary, with concomitant pollution issues (Moores, 2015). The increase in graphite demand for EVs in recent years has coincided with a lowering demand in the steel industry (the major user of medium flake natural graphite), which has kept prices low (Moores, 2015). However, it is clear that there will not be enough graphite to supply EV batteries if historic trends continue through to 2030 (Ballinger et al., 2019). The supply chain of natural graphite is highly localized in China, which accounts for 65 percent of total flake graphite produced globally, thus representing a resource security issue. Furthermore, Chinese production has recently been cut due to environmental issues. China also supplies a large portion of synthetic graphite, which accounts for 45 percent of the graphite used in EV batteries. Silicon has been considered as a replacement, but degrades quickly compared to graphite and has its own environmental issues, as previously noted.

Cobalt mining represents a particularly concerning social issue. The increase in supply required to meet EV targets creates problems given the complexity of the cobalt supply chain. Approximately 90 percent of cobalt production is a by-product of nickel or copper mining. Further, approximately 50 percent of cobalt is produced in the Democratic Republic of the Congo (DRoC). DRoC's high market share of production represents a significant resource security issue given the geopolitical context.

The DRoC is politically unstable and human rights violations exist in the country's cobalt mining practices, particularly in terms of the exploitation of children. An International Labour Organization (2017) report noted:

> Children were also exposed to the worst forms of child labour in the mines of Katanga and East Kasai, where around 40,000 children were working under the oversight of military units on mineral extraction. They worked in mines for up to 12 hours a day, for US$1 or $2, in extremely hot temperatures, without the slightest protection and in contact with high concentrations of cobalt. (p. xx)

Finally, copper and aluminum content for the anode and cathode represent concerns. Copper is a key mineral for both permanent magnet and induction motors. EVs use four times as much copper as conventional vehicles, not including recharging infrastructure and electricity generation (Narins, 2017). Ballinger et al. (2019, p.7) commented, "Further research is thus required to develop electric vehicle (and low carbon technologies more broadly) deployment pathways that are resilient to real world material supply chain risks."

Lifetime issues: Currently there is a danger of greenwashing, where electricity derived from fossil fuels is laundered into EVs (de Freitas Netto et al., 2020). Valley-filling (charging at night) and peak shaving (feeding the grid from the battery at peak periods), can help. Increasing the lifetime of batteries could also significantly improve the environmental sustainability of electric mobility. Moreover, battery efficiency, more than battery weight, is a key factor in reducing the impacts of the battery-use phase.

EoL issues: An EV battery needs replacement after losing around 20 to 30 percent of its capacity, or after around 4,000 charge cycles, or 120,000 kilometers of driving. This equates to approximately 10 years. Given the expense and the environmental and social issues surrounding its production, this is a significant issue.

High recycling costs limit lithium recovery from the electrolyte ($LiPF_6$). The pyrometallurgy approach is the most frequently used method since it is rapid and readily scaled up. However the energy consumption is high and lithium is lost in the slag. Furthermore, there is release of CO_2, CO, SO_2, and dioxins (C. Liu et al., 2019). A study by Jiao and Evans (2016) identified current EV practices and market uptake barriers as unsustainable from economic, social, and environmental perspectives.

Hydrogen

Hydrogen is the third most abundant element in the Earth's crust and the most abundant element in the universe, totaling 75 percent of all matter. It forms the fuel for our neighboring star, feeding its fusion reactor. Hydrogen gas is not found in our atmosphere. Hydrogen has the highest energy content per unit mass of all the elements (Baykara, 2018). On Earth, it is invariably bound up in chemical compounds with other elements. It must, therefore, be produced from other hydrogen-containing sources using energy, such as electricity or heat.

Production issues: The energy input for hydrogen production is always greater than the energy output from hydrogen. Problematically, fossil fuels constitute 96 percent of the substrates for hydrogen (H_2) production (grey hydrogen) currently. Worldwide, overall CO_2 emissions from hydrogen plants approach nearly half a billion tons per year as part of global production of some 60 million tons of H_2 per year (Muradov, 2017). It would clearly be preferable to utilize some form of solar-driven water electrolysis, releasing oxygen and hydrogen (green hydrogen), but this is some way from being commercially available at present. At the present time the cost of hydrogen from photovoltaic electricity through electrolysis is 25 times higher than that of hydrogen produced from coal or natural gas plants.

Lifetime issues: Other risks include an increase in H_2 in the atmosphere, increasing water vapor, and decreasing stratospheric temperature, which would decrease ozone production. In the mesosphere, noctilucent clouds alter the albedo effect while potentially altering soil microbial communities, where H_2 is a nutrient (Tromp et al., 2003). Muradov (2017) concluded that: "achieving near-zero CO_2 emissions from hydrogen generation processes in the mid-to-long term future appears to be feasible, but will be extremely challenging" (p. 14084).

Biofuels

Biofuels are defined as high-density energy carriers derived from biomass transformation. Globally, the number of people in rural communities utilizing biomass as their main energy source is projected to rise to 2.8 billion by 2030 (Kaygusuz, 2012). An increasing use of biomass is in biofuel synthesis. In 2016, global biofuel production reached 2.35 million barrels per day (Mbd^{-1}) and represented 4 percent of world road transport fuel.

Production issues: Fertilizers used to grow biomass incur a CO_2 cost because ammonia production requires large amounts of energy for its synthesis and, in combination with applied phosphorus, contributes significantly to eutrophication. Therefore, while trying to reduce greenhouse gas emissions, the overall environmental sustainability of bio-ethylene suffers from increases in other environmental impacts (Alonso-Fariñas et al., 2018). Furthermore, more fuel is needed to cover distances due to a lower energy density of biofuels compared to traditional fuels. Not only is high-grade land used, meaning it is unavailable for food production, but actual food crops are used as the biomass.

Lifetime issues: A 100 percent increase in biomass consumption (tonnes per capita) increases CO_2 emissions (tonnes per capita) within the range of 2 to 47 percent (Solarin et al., 2018). Solarin et al. (2018) recognized "the necessity of substituting fossil fuels with other types of renewable energy (such as hydropower) rather than biomass energy for reduction of emission to be achieved" (p. 22641).

As an example of issues relating to biofuels, wood pellets release higher amounts of carbon monoxide and particulate matter when combusted than does coal (Wang et al., 2017). Any concept of carbon neutrality is also questionable as forest replenishment from wood pellet production takes many decades, leading to lost forest productivity (Nian, 2016). Furthermore, mature forests play many other significant roles in environmental and ecological terms and take up to 50 years before fully deploying these roles. Even if carbon neutrality were achieved, this merely maintains the current carbon levels rather than diminishing them.

Alternative uses of wood, such as in construction, often offer larger reductions in greenhouse gases, as long-lived wood products store carbon for many years, thus achieving greater substitution benefits than bioenergy (Smyth et al., 2014). More generally, it has been pointed out that "the Earth simply has too little or no biomass to spare in the long run" (Patzek, 2008, p.19).

The use of microalgae as biofuel has recently been examined. Microalgae produce much more oil in much less space, reducing competition for land with agriculture or natural habitat. Corn requires 1,540 million hectares (Mha) of land to produce 172 liters of oil. In contrast, microalgae would need 2 Mha of land area to yield 137,000 liters of biodiesel (Chisti, 2007). However, numerous limitations and issues arise, including eutrophication, the need for large amounts of water, and harvesting difficulties. Total energy consumption is higher than total energy production in the de-watering step ($NER < 1$) (Hognon et al., 2015). Another problem is the fact that open water systems allow the breeding of vectors of dengue fever and other disease-carrying vectors. Finally, pyrolysis oil obtained from microalgae is acidic, unstable, viscous, and contains solids.

Marine Energy

Around 72 percent of the planet's surface is covered in water, most of it marine. Marine renewable energy (MRE) sources include waves, ocean currents, tides, salinity gradients, and thermal differences, the latter two of which are yet to reach mainstream application. MRE (offshore wind, wave, and tidal) has the potential to deliver 7 percent of the worldwide energy demand (Isaksson et al., 2020).

Construction issues: Some 60 percent of the world's oceans lie outside of national boundaries. This potentially results in complex claims of ownership. What if one nation's technology intercepts energy normally incident upon another?

MRE is currently extremely expensive to harvest. Allan et al. (2011) stressed that cost reduction is essential if MRE is to succeed. However, fossil fuel subsidies somewhat skew these estimates. Many of the supply chain issues previously noted for other renewable energy options also exist for MRE (Table 1). Rodier and Clare (1992) noted that during the construction of La Rance tidal power plant, "The total closure of the estuary between 1963 and 1966 during the construction of the plant caused the almost complete disappearance of the original species" (pp. 307–308).

Lifetime issues: Large MRE technologies alter the local flow hydrodynamics, impacting bypass currents, wakes, mixing, turbulence, sediment transport, littoral drift, scour, turbidity, seabed morphology, biodiversity, pollutant levels in biota, food availability, and water quality (see Bonar et al., 2015 and references therein). In addition, infringement of tribal fishing rights, acoustic and electromagnetic harassment of sea life, and interrupted migratory pathways, particularly in estuaries, all must be addressed (Dreyer et al., 2019).

Borthwick (2016) sums up the challenges as follows:

> The global challenge remains of how to exploit the MRE seascape in order to power whole cities by ocean energy in a way that is sustainable, robust, and cost-effective. As in the industrial revolution, a new generation of engineers is required that possesses the ingenuity and boldness to meet this global challenge. (p. 76)

Nuclear Energy

Almost all of life's energy is derived from nuclear energy from our neighboring star, as is almost all of the energy produced by humankind (with the exception of marine (lunar), hydrogen, and geothermal energy). If safely managed, nuclear power has the significant advantage of having an extremely high-power density (nuclear: up to 4,000W/m^2; solar photovoltaic: 4 to 10W/m^2; wind: 0.5 to 1.5W/m^2; biomass: 0.5 to

0.6 W/m^2) (Smil, 2010). Globally, around 6 percent of energy and 16 percent of electricity is harnessed from nuclear energy (Nazir et al., 2019).

The energy return on investment (EROI) is also far higher for nuclear than other power generation technologies (distributed solar: 1.6; biomass: 3.5; wind: 3.9; utility solar: 9; hydro: 35; nuclear: 75) (Weißbach et al., 2013). In terms of lifetime carbon dioxide release, nuclear power returns the best figures: 9 gCO_2/kWh e compared to wind (11), hydro (16), biomass (17), and solar (30) (McCombie & Jefferson, 2016). Benefits include energy security, consistent cost (free from cartels), low CO_2 and particulate pollution, and the potential to underpin a generation of hydrogen energy for transport. France, Lithuania, Slovakia, and Belgium all produce over 50 percent of their electricity from nuclear power.

Construction issues: Construction times are lengthy (between 64 and 146 months) (Ramana, 2009). The mining and milling of uranium-235 is energy-intensive and uranium-235 stocks are depleting (Nuclear Agency and International Atomic Energy Agency, 2018).

Lifetime issues: Nuclear energy is perhaps the most divisive issue in the energy debate. Humanity is one of the most radiosensitive organisms on the planet (Skene, 2011). Alexakhin (2013) concluded that "the development of nuclear power requires systemic documentation that would harmonize the principles of the regulation of the admissible radiation effects in man on the one hand and the environment on the other" (p. 306). A small number of catastrophic failures have terrified the populace, while nuclear fission technologies underpin nuclear weapon development. Although fatalities linked to a nuclear explosion are feared, the worst energy disaster by far was the failure of a hydro dam, along with a further 61 dams at Banqiao-Shimantan, in Henan province, in 1975, in which between 85,600 to 260,000 people died (Burgherr et al., 2013). In comparison, the worst nuclear power plant disaster, the Kyshtym disaster at Mayak, Soviet Union, in 1957, accounted for an upper estimate of 9,000 lives. Chernobyl deaths are estimated at 34,000, including post-explosion deaths from cancer, based on 0.057 cancer deaths per Sievert (Ramana, 2009). However, it is unknown how many people ultimately suffered from nonlethal cancer and damage to reproductive tissues. Fundamentally, the risks related to nuclear fission are deemed unacceptable in many societies.

Thermal discharge from nuclear reactors has been shown to alter the population dynamics of the most abundant species, reduce species richness of algal and zoobenthic organisms, and to increase the abundance of opportunistic species (Teixeira et al., 2009). There are significant and legitimate concerns over national security given that nuclear weapons can be developed simultaneously.

EoL issues: Decommissioning has major impacts on acidification, human toxicity, and photochemical ozone creation potentials (Siddiqui & Dincer, 2017) in addition to the challenges of storing the radioactive waste.

Nuclear Fission Nuclear fusion, which combines two light atoms such as deuterium and tritium rather than splitting heavy atoms such as uranium, can deliver energy with much less radiation and nuclear waste and without the risk of potentially cataclysmic explosions. While advances continue to be made in terms of nuclear fusion, the energy input still exceeds the energy output, and thus it is likely some way off before it can become a viable process. Beyond this, tritium availability may also pose problems (Pearson et al., 2018).

Discussion

From the results of the literature review, summarized in Table 1, it can clearly be seen that the portfolio of renewable energy technologies poses multiple, significant threats to a truly sustainable future. If we adopt a business-as-usual approach and continue with the current technologies in their present forms, we must anticipate an explosion of landfill waste full of glass fiber, EV batteries, leaching toxins, and environmental and ecological perturbation. We must acknowledge supply chains that are creating toxic contexts for the people located near REM mines, lithium mines, and cobalt mines. Ecotoxicity and environmental perturbation should be recognized as an ongoing issue under current renewable energy practices, as should the threats to indigenous lands, cultural sites, and fragile ecosystems. Potential risks of geopolitical interference in our supply chains should also be acknowledged.

Surely this is not a path that we would choose to pursue, yet ignorance of these issues does not remove accountability from us. Instead, a number of significant regulatory, policy, and research priorities are suggested, detailed in Table 2; these should be implemented urgently. Before investing further in these flawed technologies, emphasis should be placed on correcting the flaws.

Many of the toxic and insecure supply chains are used to maximize

Table 2. Regulatory, Policy and Research Priorities to Address Sustainable Energy Issues

Technology	Regulatory, policy, and research priorities
Wind	Urgent policy framework and research to avoid landfill time bomb; regulations on recycling; improved floating platforms for offshore; explore alternative turbine materials such as wood, bamboo, and lactic acid; regulated reduction in blade size; regulations on locations, avoiding migration routes; radar lookout warning of inbound wildlife.
Hydro	Policies to drive distributed electric grid, encompassing micro-hydroelectric units; urgent research into threat of climate destabilization on hydrological cycles and their potential disruption to dams.
Geothermal/ GSHP	Policy to establish openly available global geo-referenced information base on critical geological conditions; shift to binary rather than open-loop; research to address groundwater contamination, particularly of arsenic; research to reduce thermal discharge.
PV	Urgent, fundamental re-examination of recyclability of modules and supply chain issues; regulations placing utility PV facilities on brown space; implementation of a clear, easy route for distributed PV module recycling; research into improving the extraction of silicon.
EV	Full investigation into indigenous people's well-being and welfare in fragile high altitude lithium brine locations; EoL policy, regulations, and research; full audit of environmental, ecological, and human implications of alternative lithium sources.
Hydrogen	Policy to move away from grey hydrogen completely; investment in green hydrogen research and development; research on atmospheric and soil impacts of elevated hydrogen levels.
Biomass	Recognition that biomass cannot be a significant player due to particulate matter, land/water/fertilizer use, and issues around carbon neutrality; policy shift to emphasis on living biomass, not biofuel, based upon ecological, hydrological, and carbon capture grounds.
Marine	Research to avoid ecocide with construction of tidal barriers; resolution of legal issues relating to ownership; increased funding needed across the sector; research exploring distributed micro-marine approach, akin to hydro power.
Nuclear	Fundamental research to fully revisit design; increased use of robots; strict regulations on location, avoiding areas of geological and tsunami risk; closure of potentially at-risk plants; research addressing peak uranium-235.

efficiency, such as glass fiber rotors, permanent magnet motors, and lightweight batteries. Options do exist. Alternative, plant-based materials can be used to make the rotors (Holmes et al., 2009; Mack et al., 2019). Permanent magnet motors can be replaced by electromagnets, freeing us from the REM burden. Smaller rotors will be less of a threat to wildlife.

Stopping production of CdTe PV modules while improving silicon extraction methods will greatly reduce the environmental impact. Shifting to distributed grid approaches (Edenhofer et al., 2011), including micro-hydro and micro-marine technologies, will increase community independence, integration, and accountability, reducing the pressure on utility energy supply and avoiding most of the current issues of large-scale technology.

This brings us to a fundamental point: The priority must be to use less energy. Reducing waste is recognized as a key strategy in terms of reducing the intensity of agriculture, where some 40 percent of food is wasted from farm to kitchen. Agriculture is also one of the most polluting and energy-consuming industrial sectors, primarily because of its dependence upon the Haber-Bosch process used in producing nitrogen fertilizers. Fertilizers have destructive impacts upon the aquatic environments and forests where they end up, leading to the collapse of fisheries and to toxic algal blooms (Celikkol Erbas & Guven Solakoglu, 2017).

Methane production from cattle is another significant concern. While this article is not focused on the energy–agriculture nexus, it is worth noting that all energy sinks, particularly agriculture, must move away from excess energy consumption. Nitrogen fertilizers release the powerful greenhouse gas, nitrous oxide. Inter-cropping, rotation, agroforestry, and fallow years have all been shown to draw down CO_2 by increasing soil organic matter while allowing a significant reduction in applied fertilizers and increasing the water-holding capacity of the soil.

We need to recognize that our wasteful approach to energy must also become a thing of the past. By doing this, we can substitute highly efficient but toxic supply chains with cleaner, less efficient supply chains, allowing us to meet the reduced energy needs and vastly shrink the ecological, environmental, and social footprints of our technologies.

Fundamentally, it is our overconsumption of energy and resources that are the largest problem. As we have seen, all approaches to energy provision have implications for our environment and society. The more basic point is that we need to reduce our energy expenditure. Central to this is re-examining how we use energy. Western development represents high-energy lifestyles as part of its messaging, setting this as a standard for the rest of the world. Yet many of the so-called developing nations have much greater energy efficiency and a much lower environmental impact. Measures to dissuade people from energy use by increasing fuel prices directly impact on the poor, leading to fuel poverty.

In terms of overpopulation, central to any understanding here is the issue of heterogeneity. There is a great diversity of consumption patterns across the globe, with many people consuming very little while others (mostly in the West) consuming vast amounts of resources. Thus we need to be aware that large populations do not automatically equate to large consumption. However, it is also true that smaller populations consume less than large populations, wherever they are located. What is imperative is that we emphasize cutting consumption primarily, and do not set the high consumption of the West as the standard that represents well-being and success.

Accountability, both at the individual consumer and industry levels, is needed, wherein the internet-of-things (IoT) and artificial intelligence (AI) can create and evidence transparent supply chains with social and environmental justice (Skene, 2020a). Localism, in terms of energy production, has many benefits, including reducing reliance on huge energy production facilities such as vast dams for hydropower and large-scale wind farms. Decentralized energy production also offers the benefits of tying a community to its natural resources and of being more accountable in their consumption of energy.

Most settlements are built near streams and rivers, offering the potential for small hydropower plants (SHP). However, there is no international agreement as to what constitutes small, and many of the larger SHPs can quite significantly impact fish and micro-invertebrates (Couto & Olden, 2018). Micro-hydropower units (generating < 200kW energy) have significant advantages in terms of reduced ecological impact and can be used in much smaller streams and in off-grid, remote areas, reducing reliance upon biomass (Bhandari et al., 2018; Butchers et al., 2020).

Small wind turbines (SWT) have energy outputs of between 0.2 and 100 kW. Benefits of SWT use must, however, address the same issues related to large wind turbines in terms of materials and end-of-life issues. In terms of social justice, SWTs and micro-hydropower units both offer access to energy for rural, isolated communities, greatly improving their well-being without significant environmental damage.

Cogeneration systems produce both thermal and electrical (or mechanical) energy from the same primary energy source. This can be 40 percent more efficient than generating heat and power separately. Examples include steam turbine generation using biomass. However, criticisms of the underlying methods, in this case biomass, still must be addressed. Micro-cogeneration, again operating at a more local level, has less impact than larger cogeneration schemes (Pehnt, 2008).

The additional expenditure necessitated by the actions highlighted in Table 2 can be delivered by employing some of the US $1 trillion annual subsidies currently invested in the fossil fuel supply chain (International Energy Agency, 2017a, 2017b). Reducing fossil-fuel subsidies will also level the financial playing field among different energy technologies, helping markets identify real economic advantages (United Nations Environment Programme, 2015). However, this must be done in such a way as to avoid fuel poverty.

Conclusion

This article represents a critique of the major renewable energy technologies in terms of their production, lifetime, and EoL. Many significant issues, identified in Table 1, together represent a threat to any conception of a sustainable future. This article suggests that our fixation with carbon is a potentially existential issue in itself. Solving only the carbon issue will be unlikely to avert disaster and solving it while exacerbating other issues will only accelerate the threat, as exemplified by current renewable energy technology.

A business-as-usual path, built upon such flawed foundations, carries with it significant baggage in terms of environmental and social well-being. With calls to massively expand the EV and wind energy sectors, such concerns become even more relevant.

In summary, any technology claiming to contribute to a sustainable future must demonstrate ecological resonance in that it restores the functionality and sovereignty to nature, and social resonance in that it restores the functionality and sovereignty to society. Current renewable energy technologies clearly do not meet these standards.

As McCombie and Jefferson (2016,) have suggested, "Limitations on sustainability posed by the environmental and human impacts of energy technologies should be factored into policies that support certain technologies over others" (p. 768). To be fit-for-purpose, a range of regulatory, policy, and research priorities have been identified (Table 2). Underpinning these are some key elements.

Firstly, technology must be situated within the Earth system, where tradeoffs underpin system functioning. Any attempt to optimize the design of a wind turbine for efficiency and profitability as a stand-alone project will always fail, as component suboptimality is a fundamental property of complex systems (Skene, 2020b). Designing within the system must be the priority. Secondly, the recyclability of design outcomes must be a priority. This, again, will demand suboptimality of functionality. Solar panels and glass/carbon fiber turbines are an example here. All recycling issues begin with the design brief.

Thirdly, material substitution will address many of the worst issues facing us. Electromagnets should replace permanent magnets. CdTe batteries in EVs and glass and carbon fibers in turbines should be phased out. Fourthly, supply chain transparency must be achieved. The use of cobalt should be immediately halted until child labor is removed from the supply chain. The IoT and AI together can provide the data from all parts of a supply chain, allowing accountability for producers and consumers of our energy. Fifthly, distributed grids, where communities are more responsible for the choices and impacts of their energy production, will again increase accountability, shortening the supply chain and reducing damage to the environment.

Finally, and most fundamentally, emphasis must be heavily placed on reducing energy use. This will allow more room for sustainable solutions. This will require government intervention and significant public education, removing barriers to such changes (see Gifford, 2011). Again, significant funding will be needed for this, but the financing potential exists.

Current renewable energy sources all have very significant Achilles' heels (see Table 1). A sustainable future must aim for environmental and societal recovery, where second-best is not good enough. This requires sub-optimality, supply chain transparency, and the removal of the toxic footprints still present in manufacture, operation, and EoL. It requires a recognition that much is left to do, and the willingness to make the necessary investment to do it. Before plowing billions into these new renewable technologies, regulations, policies, and research must ensure that they are fit-for-purpose, and truly deliver a sustainable future for all.

Funding Information

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Author Disclosure Statement

No competing financial interests exist.

References

Alexakhin, R.M. (2013). Topical environmental problems of nuclear power. *Atomic Energy, 114*, 301-307. https://doi.org/10.1007/s10512-013-9715-x

Allan, G.J., Gilmartin, M., McGregor, P.G., & Swales, K. (2011). Levelised costs of wave and tidal energy in the UK: Cost competitiveness and the importance of "banded" renewables obligation certificates. *Energy Policy, 39*, 23–39. https://doi.org/10.1016/j.enpol.2010.08.029

Alonso-Fariñas, B., Gallego-Schmid, A., Haro, P., & Azapagic, A. (2018). Environmental assessment of thermo-chemical processes for bio-ethylene production in comparison with bio-chemical and fossil-based ethylene. *Journal of Cleaner Production, 202*, 817-829. https://doi.org/10.1016/j.jclepro.2018.08.147

Azevedo, M., Campagnol, N., Hagenbruch, T., Hoffman, K., Lala, A., et al. (2018, June). Lithium and cobalt—A tale of two commodities. *Metals and Mining,* McKinsey & Company. https://www.mckinsey.com/~/media/mckinsey/industries/metals%20and%20mining/our%20insights/lithium%20and%20cobalt%20a%20tale%20of%20two%20commodities/lithium-and-cobalt-a-tale-of-two-commodities.ashx

Ballinger, B., Stringer, M., Schmeda-Lopez, D.R., Kefford, B., Parkinson, B., et al. (2019). The vulnerability of electric vehicle deployment to critical mineral supply. *Applied Energy, 255,* 113844. https://doi.org/10.1016/j.apenergy.2019.113844

Bansal, R. (2005). Electric vehicles. In A. Emadi (Ed.), *Handbook of automotive power electronics and motor drives* (pp. 55-96). CRC Press.

Barrick, K.A. (2007). Geyser decline and extinction in New Zealand—energy development impacts and implications for environmental management. *Environmental Management, 39,* 783–805. https://doi.org/10.1007/s00267-005-0195-1

Baykara, S.Z. (2018). Hydrogen: A brief overview on its sources, production and environmental impact. *International Journal of Hydrogen Energy, 43,* 10605-10614. https://doi.org/10.1016/j.ijhydene.2018.02.022

Bell, L., 1906. The utilization of natural energy. *Cassier's Magazine*, Vol. 29, pp. 466–476.

Berkhout, P.H., Muskens, J.C., & Velthuijsen, J.W. (2000). Defining the rebound effect. *Energy Policy, 28*, 425-432. https://doi.org/10.3389/fenrg.2018.00081

Bertani, R. (2016). Geothermal power generation in the world 2010–2014 update report. *Geothermics, 60*, 31–43. https://doi.org/10.1016/j.geothermics.2015.11.003

Bhagea, R., Bhoyroo, V., & Puchooa, D. (2019). Microalgae: The next best alternative to fossil fuels after biomass. A review. *Microbiology Research, 10*, 12-24. https://doi.org/10.4081/mr.2019.7936

Bhandari, R., Saptalena, L.G., & Kusch, W. (2018). Sustainability assessment of a micro hydropower plant in Nepal. *Energy, Sustainability, and Society, 8*(3), 1-15. https://doi.org/10.1186/s13705-018-0147-2

Bicer, Y., & Dincer, I., 2017. Comparative life cycle assessment of hydrogen, methanol and electric vehicles from well to wheel. *International Journal of Hydrogen Energy, 42* (6), 3767-3777. https://doi.org/10.1016/j.ijhydene.2016.07.252

Bogacka, M., Pikoń, K., & Landrat, M. (2017). Environmental impact of PV cell waste scenario. *Waste Management, 70*,198-203. https://doi.org/10.1016/j.wasman.2017.09.007

Bonar, P.A.J., Bryden, I.G., & Borthwick, A.G.L. (2015). Social and ecological impacts of marine energy development. *Renewable and Sustainable Energy Reviews, 47*, 486–495. https://doi.org/10.1016/j.rser.2015.03.068

Borthwick, A.G. (2016). Marine renewable energy seascape. *Engineering 2*, 69-78. https://doi.org/10.1016/J.ENG.2016.01.011

Bravi, M., & Basosi, R. (2014). Environmental impact of electricity from selected geothermal power plants in Italy. *Journal of Cleaner Production, 66*, 301-308. http://dx.doi.org/10.1016/j.jclepro.2013.11.015

Brøndsted, P., Lilholt, H., & Lystrup, A. (2005). Composite materials for wind power turbine blades. *Annual Review of Materials Research, 35*, 505-538. https://doi.org/10.1146/annurev.matsci.35.100303.110641

Burgherr, P., Hirschberg, S., & Spada, M. (2013). Comparative assessment of accident risks in the energy sector. In G.C. Pflug, R.M. Kovacevic, & M.T. Vespucci (Eds.), *Handbook of risk management in energy production and trading* (pp. 475-501). Springer.

Butchers, J., Williamson, S., Booker, J., Tran, A., Karki, P.B., et al. (2020). Understanding sustainable operation of micro-hydropower: A field study in Nepal. *Energy for Sustainable Development, 57*, 12-21. https://doi.org/10.1016/j.esd.2020.04.007

Calvert, A.M.C., Bishop, C.A., Elliot, R.D., Krebs, E.A., Kydd, T.M., et al. (2013). A synthesis of human-related avian mortality in Canada. *Avian Conservation and Ecology, 8*, 1. https://doi.org/10.5751/ACE-00581-080211

Celikkol Erbas, B., & Guven Solakoglu, E. (2017). In the presence of climate change, the use of fertilizers and the effect of income on agricultural emissions. *Sustainability, 9*(11), 1989. https://doi.org/10.3390/su9111989

Chan, H.Y., Riffat, S.B., & Zhu, J. (2010). Review of passive solar heating and cooling technologies. *Renewable and Sustainable Energy Reviews, 14*(2), 781-789. https://doi.org/10.1016/j.rser.2009.10.030

Chisti Y. (2007). Biodiesel from microalgae. *Biotechnolgy Advances, 25* (3), 294–306. https://doi.org/10.1016/j.biotechadv.2007.02.001

Choi, H., Jedrychowski, W., Spengler, J., Camann, D.E., Whyatt, R.M., et al. (2006). International studies of prenatal exposure to polycyclic aromatic hydrocarbons and fetal growth. *Environmental Health Perspectives, 114*, 1744–1750. https://doi.org/10.1289/ehp.8982

Choubey, P.K., Kim, M.S., Srivastava, R.R., Lee, J.C., & Lee, J.Y. (2016). Advance review on the exploitation of the prominent energy-storage element: Lithium. Part I: From mineral and brine resources. *Minerals Engineering, 89*, 119-137. https://doi.org/10.1016/j.mineng.2016.01.010

Cifuentes, L., Borja-Aburto, V.H., Gouveia, N., Thurston, G., & Davis, D.L. (2001). Assessing the health benefits of urban air pollution reductions associated with climate change mitigation (2000–2020): Santiago, São Paulo, México City, and New York City. *Environmental Health Perspectives, 109,* 419–425. https://doi.org/10.1289/ehp.01109s3419

Clark, C.E., Harto, C.B., Sullivan, J.L., & Wang, M.Q. (2011). *Water use in the development and operation of geothermal power plants.* US Dept. of Energy, Office of Scientific and Technical Information, Report No. ANL/EVS/R-10/5. https://doi.org/10.2172/1013997

Cleasby, I.R., Wakefield, E.D., Bearhop, S., Bodey, T.W., Votier, S.C., et al. (2015). Three-dimensional tracking of a wide-ranging marine predator: Flight heights and vulnerability to offshore wind farms. *Journal of Applied Ecology, 52*, 1474-1482. https://doi.org/10.1111/1365-2664.12529

Couto, T.B. & Olden, J.D. (2018). Global proliferation of small hydropower plants–science and policy. *Frontiers in Ecology and the Environment, 16*(2), 91-100. https://doi.org/10.1002/fee.1746

Department of Energy and Climate Change. (2011). *Overarching national policy statement for energy (EN-1)*. Presented to Parliament pursuant to Section 5(9) of the Planning Act 2008. The Stationery Office, London. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1015233/en-1-draft-for-consultation.pdf

de Freitas Netto, S.V., Sobral, M.F.F., Ribeiro, A.R.B., & da Luz Soares, G.R. (2020). Concepts and forms of greenwashing: A systematic review. *Environmental Sciences Europe, 32*, 1-12. https://doi.org/10.1186/s12302-020-0300-3

Dreyer, S.J., Beaver, E., Polis, H.J., & Jenkins, L.D. (2019). Fish, finances, and feasibility: Concerns about tidal energy development in the United States. Energy Research & Social Science, 53, 126-136. https://doi.org/10.1016/j.erss.2019.02.024

Ebensperger, A., Maxwell, P., & Moscoso, C. (2005). The lithium industry: Its recent evolution and future prospects. *Resoures Policy, 30*(3), 218–231. https://doi.org/10.1016/j.resourpol.2005.09.001

Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Matschoss, P., et al. (2011). *Renewable energy sources and climate change mitigation*. Cambridge University Press. http://dx.doi.org/10.1017/CBO9781139151153

Environmental Protection Agency. (2020). *The green book nonattainment areas for criteria pollutants*. https://www.epa.gov/green-book

Fleuchaus, P., & Blum, P. (2017). Damage event analysis of vertical ground source heat pump systems in Germany. *Geothermal Energy, 5*, 10. https://doi.org/10.1186/s40517-017-0067-y

Fleuchaus, P., Godschalk, B., Stober, I., & Blum, P. (2018). Worldwide application of aquifer thermal energy storage—A review. *Renewable and Sustainable Energy Reviews, 94*, 861–876. https://doi.org/10.1016/j.rser.2018.06.057

Førsund, F.R. (2015). *Hydropower economics* International Series in Operational Research & Management Science, Volume 217. Springer.

Giambastiani, B.M.S., Tinti, F., Mendrinos, D., & Mastrocicco, M. (2014). Energy performance strategies for the large scale introduction of geothermal energy in residential and industrial buildings: The GEO.POWER project. *Energy Policy, 65*, 315-322. https://doi.org/10.1016/j.enpol.2013.10.008

Gifford, R. (2011). The dragons of inaction: Psychological barriers that limit climate change mitigation and adaptation. *American Psychologist, 66*, 290-302. https://doi.org/10.1037/a0023566

Ginder, R.S., & Ozcam, S. (2019). Recycling of commercial E-glass reinforced thermoset composites via two temperature step pyrolysis to improve recovered fiber tensile strength and failure strain. *Recycling, 4*, 24. https://doi.org/10.3390/recycling4020024

Gischig, V., Wiemer, S., & Alcolea, A. (2014). Balancing reservoir creation and seismic hazard in enhanced geothermal systems. *Geophysics Journal International, 198*(3), 1585–1598. https://doi.org/10.1093/gji/ggu221

Gluyas, J.G., Adams, C.A., Busby, J. P., Craig, J., Hirst, C., et al. (2018). Keeping warm: A review of deep geothermal potential of the UK. *Proceedings of the Institution of Mechanical Engineers, Part A:Journal of Power and Energy, 232*(1), 115-26. https://doi.org/10.1177/0957650917749693

GM Heritage Center. (2019). *GM hydrogen fuel cell vehicles*. https://www.gmheritagecenter.com/featured/Fuel_Cell_Vehicles.html

Grove, W.R. (1839). On a small voltaic battery of great energy; some observations on voltaic combinations and forms of arrangement; and on the inactivity of a copper positive electrode in nitro-sulphuric acid. *The London Edinburgh and Dublin Philosophical Magazine and Journal of Science, 15*, 287-293.

Global Wind Energy Council/Global Wind Organisation. (2020). *Powering the future: Global offshore wind workforce outlook 2020-2024*. https://gwec.net/powering-the-future-report/#:~:text=The%20Global%20Wind%20Energy%20Council%20%28%20GWEC%29%20and,collaboration%20with%20Renewables%20Consulting%20Group%20%28%20RCG%20%29

Harjanne, A., & Korhonen, J.M. (2019). Abandoning the concept of renewable energy. *Energy Policy, 127*, 330-340. https://doi.org/10.1016/j.enpol.2018.12.029

Hastings, R. (2020). Passive solar heating in the built environment. In V. Loftness (Ed.), *Encyclopedia of sustainability science and technology series. Sustainable built environments* (pp. 351-382). Springer. https://doi.org/10.1007/978-1-0716-0684-1_372

Hayes, M. (2013). Bats killed in large numbers at United States wind energy facilities. *BioScience. 63*(12), 975-979. https://doi.org/10.1525/bio.2013.63.12.10

Henry, J. (1831). On a reciprocating motion produced by magnetic attraction and repulsion. *Silliman's American Journal of Science, 20*, 340–343.

Hognon, C., Delrue, F., & Boissonnet, G. (2015). Energetic and economic evaluation of *Chlamydomonas reinhardtii* hydrothermal liquefaction and pyrolysis through thermochemical models. *Energy, 93*, 31–40. http://dx.doi.org/10.1016/j.energy.2015.09.021

Holmes, J.W., Brøndsted, P., Sørensen, B.F., Jiang, Z.H., Sun, Z.H., et al. (2009). Development of a bamboo-based composite as a sustainable green material for wind turbine blades. *Journal of Wind Engergy, 33*, 197–210. http://doi.org/10.1260/030952409789141053

Horikawa, T., Miura, K., Itoh, M., & Machida, K.I. (2006). Effective recycling for Nd-Fe-B sintered magnet scraps. *Journal of Alloys and Compounds, 408-412*, 1386-1390. http://dx.doi.org/10.1016/j.jallcom.2005.04.091

International Energy Agency. (2014). *World Energy Outlook, 2014.* https://www.iea.org/reports/world-energy-outlook-2014

International Energy Agency. (2017a). *World Energy Investment 2016*. IEA, Paris. https://www.iea.org/reports/world-energy-investment-2016

International Energy Agency, 2017b. *World energy outlook 2017.* IEA, Paris. https://www.iea.org/reports/world-energy-outlook-2017

International Energy Agency. (2018). *World energy balances: Overview*. https://www.iea.org/reports/world-energy-balances-overview

International Energy Agency. (2020). Photovoltaic Power Systems Programme. *Snapshot 2020.* https://iea-pvps.org/snapshot-reports/snapshot-2020/

International Labour Organization. (2017). *Worst forms of child labour convention, 1999 (No. 182) - Democratic Republic of the Congo.* Normex. Individual Case (CAS) - Discussion: 2017, Publication: 106th ILC session (2017). http://www.ilo.org/dyn/normlex/en/f?p=NORMLEXPUB:13100:0::NO::P13100_COMMENT_ID:3331022

Intergovernmental Panel on Climate Change. (2014). Summary for policymakers. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, et al. (Eds.), *Climate change 2014, Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

International Renewable Energy Agency and the International Energy Agency Photovoltaic Power Systems Programme. (2016). *End-of-life management: Solar photovoltaic panels*. https://www.irena.org/publications/2016/Jun/End-of-life-management-Solar-Photovoltaic-Panels

Isaksson, N., Masden, E.A., Williamson, B.J., Costagliola-Ray, M. M., Slingsby, J., et al. (2020). Assessing the effects of tidal stream marine renewable energy on seabirds: A conceptual framework. *Marine Pollution Bulletin, 157*, 111314. https://doi.org/10.1016/j.marpolbul.2020.111314

Jaber, S. (2013). Environmental impacts of wind energy. *Journal of Clean Energy Technology, 1*, 251-254. https://doi.org/10.7763/JOCET.2013

Jackson, S., & Sleigh, A. (2000). Resettlement for China's Three Gorges Dam: Socio-economic impact and institutional tensions. *Communist Post-Communist Studies, 33*, 223-241. https://doi.org/10.1016/S0967-067X(00)00005-2

Jensen, J.P., & Skelton, K. (2018). Wind turbine blade recycling: Experiences, challenges and possibilities in a circular economy. *Renewable Sustaintainable Energy Review, 97*, 165–76. https://doi.org/10.1016/j.rser.2018.08.041

Jiao, N., & Evans, S. (2016). Secondary use of electric vehicle batteries and potential impacts on business models. *Journal of Industrial and Production Engineering, 33*, 348-354. https://doi.org/10.1080/21681015.2016.1172125

Jungbluth, N., Stucki, M., Frischknecht, R., & Buesser, S. (2009). Photovoltaics. In R. Dones (Ed.), *Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz* (Life cycle assessments of energy systems: Basics for the ecological comparison of energy systems and the inclusion of energy systems in life cycle assessments for Switzerland). *Ecoinvent Report*, *6*, XII. Swiss Centre for Life Cycle Inventories.

Kaldellis, J.K., & Zafirakis, D. (2011). The wind energy (r)evolution: A short review of a long history. *Renewable Energy, 36*, 1887-1901. https://doi.org/10.1016/j.renene.2011.01.002

Kaygusuz, K. (2012). Energy for sustainable development: A case of developing countries. *Renewable and Sustainable Energy Reviews, 16*(2), 1116-1126. http://dx.doi.org/10.1016/j.rser.2011.11.013

Kristmannsdóttir, H., & Armannsson, H. (2003). Environmental aspects of geothermal energy utilization. *Geothermics, 32*, 451–461. http://dx.doi.org/10.1016/S0375-6505(03)00052-X

Lamnatou, C., & Chemisana, D. (2017). Photovoltaic/thermal (PVT) systems: A review with emphasis on environmental issues. *Renewable Energy 105*, 270-287. https://doi.org/10.1016/j.renene.2016.12.009

Latunussa, C., Ardente, F., Blengini, G.A., & Mancini, L. (2016). Life cycle assessment of an innovative recycling process for crystalline silicon photovoltaic panels. *Solar Energy Materials Solution Cells, 156*, 101-111. http://dx.doi.org/10.1016/j.solmat.2016.03.020i

Leahy, P.G. (2019, October 1-6). *End-of-life options for composite material wind turbine blades: Recover, repurpose or reuse?* Proceedings from the 14th Sustainable Development of Energy, Water and Environment Systems (SDEWES) Conference, Dubrovnik, Croatia (pp. 1-9).

Lemieux, P.M., Lutes, C.C., & Santoianni, D.A. (2004). Emissions of organic air toxics from open burning: A comprehensive review. *Progress in Energy Combustion Science, 30*(1), 1-32. http://doi.org/10.1016/j.pecs.2003.08.001

Lettenmaier, D.P., & Gan, T.Y. (1990). Hydrologic sensitivities of the Sacramento San Joaquin River Basin, California, to global warming. *Water Resources Research, 26*(1), 69–86. https://doi.org/10.1029/WR026i001p00069

Li, K., Bian, H., Liu, C., Zhang, D., & Yang, Y. (2015). Comparison of geothermal with solar and wind power generation systems. *Renewable and Sustainable Energy Review, 42*, 1464–74. https://doi.org/10.1016/J.RSER.2014.10.049

Liu, C., Lin, J., Cao, H., Zhang, Y., & Sun, Z. (2019). Recycling of spent lithium-ion batteries in view of lithium recovery: A critical review. *Journal of Cleaner Production, 228*, 801-813. https://doi.org/10.1016/j.jclepro.2019.04.304

Liu, P., & Barlow, C.Y. (2017). Wind turbine blade waste in 2050. *Waste Management, 62*, 229-240. https://doi.org/10.1016/j.wasman.2017.02.007

Liu, W., Agusdinata, D.B., & Myint, S.W. (2019). Spatiotemporal patterns of lithium mining and environmental degradation in the Atacama Salt Flat, Chile. *International Journal of Applied Earth Observation and Geoinformation, 80*, 145-156. https://doi.org/10.1016/j.jag.2019.04.016

Mack, D., Schätzle, S., Traa, Y., & Klemm, E. (2019). Synthesis of acrylonitrile from renewable lactic acid. *Chemistry-Sustainability-Energy-Materials, 12*(8), 1653-1663. https://doi.org/10.1002/cssc.201802914

Mancheri, N.A., Sprecher, B., Bailey, G., Ge, J., & Tukker, A. (2019). Effect of Chinese policies on rare earth supply chain resilience. *Resources Conservation and Recycling, 142*, 101-112. https://doi.org/10.1016/j.resconrec.2018.11.017

Marvel, K., Kravitz, B., & Caldeira, K. (2013). Geophysical limits to global wind power. *Nature Climate Change, 3*, 118-121. https://doi.org/10.1038/nclimate1683

McCombie, C., & Jefferson, M. (2016). Renewable and nuclear electricity: Comparison of environmental impacts. *Energy Policy, 96*, 758-769. https://doi.org/10.1016/j.enpol.2016.03.022

Mickey, C.D. (1981). Solar photovoltaic cells. *Journal of Chemical Education, 58*(5), 418. https://doi.org/10.1021/ed058p418

Miller, L.M., & Keith, D.W. (2018). Climatic impacts of wind power. *Joule 2*, 2618–2632. https://doi.org/10.1016/j.joule.2018.09.009

Moores, S. (2015, October 1).The battery supply chain in a lithium-ion revolution. *Benchmark Mineral Intelligence.* https://www.vanadiumcorp.com/images/Benchmark%20Mineral%20World%20Tour%20-%20The%20battery%20Supply%20Chain%20in%20a%20lithium-ion%20revolution.pdf

Muradov, N. (2017). Low to near-zero CO_2 production of hydrogen from fossil fuels: Status and perspectives. *International Journal of Hydrogen Energy, 42*(20), 14058-14088. https://doi.org/10.1016/j.ijhydene.2017.04.101

Nain, P., & Kumar, A. (2020). Metal dissolution from end-of-life solar photovoltaics in real landfill leachate versus synthetic solutions: One-year study. *Waste Management, 114*, 351-361. https://doi.org/10.1016/j.wasman.2020.07.004

Narins, T.P. (2017). The battery business: Lithium availability and the growth of the global electric car industry. *The Extractive Industries and Society, 4*(2), 321-328. https://doi.org/10.1016/j.exis.2017.01.013

Nazir, M.S., Mahdi, A.J., Bilal, M., Sohail, H.M., Ali, N., et al. (2019). Environmental impact and pollution-related challenges of renewable wind energy paradigm–A review. *Science of the Total Environment, 683*, 436-444. https://doi.org/10.1016/j.scitotenv.2019.05.274

Nejat, P., Jomehzadeh, F., Taheri, M., Gohari, M., & Majid, M.Z. (2015). A global review of energy consumption, CO_2 emissions, and policy in the residential sector (with an overview of the top ten CO_2 emitting countries). *Renewable Sustainable Energy Reviews, 43*, 843–862. https://doi.org/10.1016/j.rser.2014.11.066

Nian, V. (2016). The carbon neutrality of electricity generation from woody biomass and coal, a critical comparative evaluation. *Applied Energy, 179*, 1069e80. https://doi.org/10.1016/j.apenergy.2016.07.004

Norouzi, N., Fani, M., & Ziarani, Z.K. (2020). The fall of oil age: A scenario planning approach over the last peak oil of human history by 2040. *Journal of Petroleum Science and Engineering, 188*, 106827. https://doi.org/10.1016/j.petrol.2019.106827

Notter, D.A., Gauch, M., Widmer, R., Wager, P., Stamp, A., et al. (2010). Contribution of Li-ion batteries to the environmental impact of electric vehicles. *Environmental Science & Technology, 44*(17), 6550–6556. https://doi.org/10.1021/es903729a

Nuclear Agency and International Atomic Energy Agency. (2018). *Uranium resources 2018: Resources, production and demand*. Organization for Economic Cooperation and Development. https://www.oecd-nea.org/upload/docs/application/pdf/2019-12/7413-uranium-2018.pdf

Olasolo, P., Juárez, M.C., Morales, M. P., ĎAmico, S., & Liarte, I.A. (2016). Enhanced geothermal systems (EGS): A review. *Renewable and Sustainable Energy Review. 56*, 133–44. https://doi.org/10.1016/J.RSER.2015.11.031

Patzek, T.W. (2008). Can the Earth deliver the biomass-for-fuel we demand? In D. Pimentel (Ed.*), Biofuels, solar and wind as renewable energy systems: Benefits and risks*. Springer,

Paulillo, A., Striolo, A., & Lettieri, P. (2019). The environmental impacts and the carbon intensity of geothermal energy: A case study on the Hellisheiði plant. *Environment International, 133* (Part B), Article 105226. https://doi.org/10.1016/j.envint.2019.105226

Pearson, R.J., Antoniazzi, A.B., & Nuttall, W.J. (2018). Tritium supply and use: A key issue for the development of nuclear fusion energy. *Fusion Engineering and Design, 136*, 1140-1148. https://doi.org/10.1016/j.fusengdes.2018.04.090

Pehnt, M. (2008). Environmental impacts of distributed energy systems—The case of micro cogeneration. *Environmental Science & Policy, 11*(1), 25-37. https://doi.org/10.1016/j.envsci.2007.07.001

Perera, F.P., Tang, D., Wang, S., Vishnevetsky, J., Zhang, B., et al. (2012). Prenatal polycyclic aromatic hydrocarbon (PAH) exposure and child behavior at age 6–7 years. *Environmental Health Perspectives, 120*, 921-926. https://doi.org/10.1289/ehp.1104315

Pontes, J. (2019, January 31). Global top 20-December 2018. *EV Sales*. http://ev-sales.blogspot.com/2019/01/global-top-20-december-2018.html

Rabatho, J.P., Tongamp, W., Takasaki, Y., Haga, K., & Shibayama, A. (2013). Recovery of Nd and Dy from rare earth magnetic waste sludge by hydrometallurgical process. *Journal of Material Cycles and Waste Management, 15*, 171–178. https://doi.org/10.1007/s10163-012-0105-6

Raje, D., & Mujumdar, P.P. (2010). Reservoir performance under uncertainty in hydrologic impacts of climate change. *Advancement in Water Resources, 33*(3), 312-326. https://doi.org/10.1016/j.advwatres.2009.12.008

Ramana, M.V. (2009). Nuclear power: Economic, safety, health, and environmental issues of near-term technologies. *Annual Review of Environmental Resources, 34*, 127-152. http://dx.doi.org/10.1146/annurev.environ.033108.092057

Ramirez-Tejeda, K., Turcotte, D.A., & Pike, S. (2017). Unsustainable wind turbine blade disposal practices in the United States: A case for policy intervention and technological innovation. *New Solutions, 26*, 581-598. https://doi.org/10.1177/1048291116676098

Ramos-Ruiz, A., Wilkening, J.V., Field, J.A., & Sierra-Alvarez, R. (2017). Leaching of cadmium and tellurium from cadmium telluride (CdTe) thin-film solar panels under simulated landfill conditions. *Journal of Hazardous Materials, 336*, 57-64. https://doi.org/10.1016/j.jhazmat.2017.04.052

Rashad, S.M., & Ismail, M.A. (2000). Environmental-impact assessment of hydro-power in Egypt. *Applied. Energy, 65*, 285-302. https://doi.org/10.1016/S0306-2619(99)00068-9

Rodier, M., & Clare, R. (1992). *Tidal power: Trends and developments*. Thomas Telford.

Roussi, A. (2019). Gigantic Nile dam prompts clash between Egypt and Ethiopia. *Nature, 574*, 159-161. https://doi.org/10.1038/d41586-019-02987-6

Sachs, O., & Eberhard, M. (2010). *Erdgasausbruch bei einer Erdwärmesondenbohrung in Rothrist-Buchrain–ein Erfahrungsbericht* (Natural gas outbreak at an earth heatprobe borehole in Rothrist-Buchrain. A report of experience). *Bulletin fuer Angewandte Geologie (Applied Geology Bulletin, 15*, 43–51. http://doi.org/10.5169/seals-227476

Sanner, B. (2017, May 15-18). Ground source heat pumps—History, development, current status, and future prospects. Proceedings of the 12th International Energy Agency Heat Pump Conference, pp. 15-18. Rotterdam, Netherlands.

Sass, I., & Burbaum, U. (2010). Damage to the historic town of Staufen

(Germany) caused by geothermal drillings through anhydrite-bearing formations. *Acta Carsologica 39*, 233-245. https://doi.org/10.3986/ac.v39i2.96

Shen, G., Xu, B., Jin, Y., Chen, S., Zhang, W., et al. (2017). Monitoring wind farms occupying grasslands based on remote-sensing data from China's GF-2 HD satellite—A case study of Jiuquan City, Gansu province, China. *Resources, Conservation and Recycling, 121*, 128-136. https://doi.org/10.1016/J.RESCONREC.2016.06.026

Shortall, R., Davidsdottir, B., & Axelsson, G. (2015). Geothermal energy for sustainable development: A review of sustainability impacts and assessment frameworks. *Renewable Sustainable Energy Reviews, 44*, 391-406. https://doi.org/10.1016/J.RSER.2014.12.020

Siddiqui, O., & Dincer, I. (2017). Comparative assessment of the environmental impacts of nuclear, wind and hydro-electric power plants in Ontario: A life cycle assessment. *Journal of Cleaner Production, 164*, 848-860. https://doi.org/10.1016/j.jclepro.2017.06.237

Skene, K.R. (2011). *Escape from bubbleworld: Seven curves to save the Earth*. Ard Macha Press.

Skene, K.R. (2018). Circles, spirals, pyramids and cubes: Why the circular economy cannot work. *Sustainability Science 13*, 479-492. https://doi.org/10.1007/s11625-017-0443-3

Skene, K.R. (2020a). *Artificial intelligence and the environmental crisis: Can technology really save the world?* Routledge.

Skene, K.R. (2020b). No goal is an island: The implications of systems theory for the Sustainable Development Goals. *Environment Development and Sustainability, 23*, 9993-10012. https://link.springer.com/article/10.1007/s10668-020-01043-y

Skene, K.R., & Murray, A. (2017). *Sustainable economics: Context, challenges and opportunities for the 21st-century practitioner*. Routledge.

Smil, V. (2010). *Energy transitions: History, requirements, prospects.* Praeger.

Smyth, C.E., Stinson, G., Neilson, E., Lempriere, T.C., Hafer M., et al. (2014). Quantifying the biophysical climate change mitigation potential of Canada's forest sector. *Biogeosciences 11*, 3515-29. https://doi.org/10.5194/bg-11-3515-2014

Solarin, S.A., Al-Mulali, U., Gan, G. G.G., & Shahbaz, M. (2018). The impact of biomass energy consumption on pollution: Evidence from 80 developed and developing countries. *Environmental Science and Pollution Research, 25,* 22641-22657. https://doi.org/10.1007/s11356-018-2392-5

Sun, G., Li, Z., Liu, T., Chen, J., Wu, T., et al. (2017). Rare earth elements in street dust and associated health risk in a municipal industrial base of central China. *Environmental Geochemical Health, 39*, 1469-1486. https://doi.org/10.1007/s10653-017-9982-x

Teixeira, T.P., Neves, L.M., & Araújo, F.G. (2009). Effects of a nuclear power plant thermal discharge on habitat complexity and fish community structure in Ilha Grande Bay, Brazil. *Marine Environmental Research 68*(4), 188-195. https://doi.org/10.1016/j.marenvres.2009.06.004

Tester J.W. (2005). *Sustainable energy: Choosing among options*. MIT Press.

Tromp, T.K., Shia, R.L., Allen, M., Eiler, J.M., & Yung, Y.L. (2003). Potential environmental impact of a hydrogen economy on the stratosphere. *Science, 300*, 1740-1742. https://doi.org/10.1126/science.1085169

Turney, D., & Fthenakis, V. (2011). Environmental impacts from the installation and operation of large-scale solar power plants. *Renewable and Sustainable Energy Reviews, 15,* 3261–3270. https://doi.org/10.1016/j.rser.2011.04.023

Tzivian, L. (2011). Outdoor air pollution and asthma in children. *Journal of Asthma 48*, 470–481. https://doi.org/10.3109/02770903.2011

United Nations Environment Programme. (2015). *Global trends in renewable energy investment 2015* (8th ed.). UNEP Collaborating Centre for Climate and Sustainable Energy Finance, Frankfurt School of Finance and Management, Germany. https://www.unep.org/resources/report/global-trends-renewable-energy-investment-2015

United Nations Climate Change. (2015, November 15). *Paris declaration on electro-mobility and climate change and call to action*. https://unfccc.int/media/521376/paris-electro-mobilitydeclaration.pdf

U.S. Department of Energy. (2018). *Clean energy*. https://www.energy.gov/science-innovation/clean-energy

Valverde, V., Clairotte, M., Bonnel, P., Giechaskiel, B., Carriero, et al. (2018). *Light-duty vehicles emissions testing.* JRC117625. Publications Office of the European Union.

Vance, E. (2009). High hopes. *Nature, 460*, 564–566. https://doi.org/10.1038/460564a

Vellini, M., Gambini, M., & Prattella, V. (2017). Environmental impacts of

PV technology throughout the life cycle: Importance of the end-of-life management for Si-panels and CdTe-panels. *Energy, 138*, 1099-1111. https://doi.org/10.1016/j.energy.2017.07.031

Wang, C., Chang, Y., Zhang, L., Pang, M., & Hao, Y. (2017). A life-cycle comparison of the energy, environmental and economic impacts of coal versus wood pellets for generating heat in China. *Energy, 120*, 374-384. https://doi.org/10.1016/j.energy.2016.11.085

Wang, S., Wang, S., & Liu, J. (2019). Life-cycle green-house gas emissions of onshore and offshore wind turbines. *Journal of Cleaner Production, 210*, 804-810. https://doi.org/10.1016/j.jclepro.2018.11.031

Weißbach, D., Ruprecht, G., Huke, A., Czerski, K., Gottlieb, S., et al. (2013). Energy intensities, EROIs (energy returned on invested), and energy payback times of electricity generating power plants. *Energy, 52*, 210-221. https://doi.org/10.1016/j.energy.2013.01.029

Wetang'ula, G.N. (2004). *Assessment of geothermal wastewater disposal effects. Case studies: Nesjavellir (Iceland) and Olkaria (Kenya) fields*. Master's thesis, University of Iceland. https://rafhladan.is/handle/10802/23472?show = full

Williams, K.R. (1994). Francis Thomas Bacon, 21 December 1904–4 May 1992. *Biographical Memoirs of the Fellows of the Royal Society, 39,* 1-18. http://doi.org/10.1098/rsbm.1994.0001

Wilmsen, B., & van Hulten, A. (2017). Following resettled people over time: The value of longitudinal data collection for understanding the livelihood impacts of the Three Gorges Dam, China. *Impact Assessment and Project Appraisal, 35*(1), 94-105. https://doi.org/10.1080/14615517.2016.1271542

Wirth, E. (1955). *Aus der Entwicklungsgeschichte der Wärmepumpe* (From the history of the development of the heat pump). *Schweizerische Bauzeitung (Swiss Construction Newspaper). 73,* 647-651.

Wong, K.V., & Tan, N. (2015). Feasibility of using more geothermal energy to generate electricity. *Journal of Energy Resources Technology, 137* (4), 041201. https://doi.org/10.1115/1.4028138

Wu, J., Lu, J., Li, L., Min, X., Zhang, Z., et al. (2019). Distribution, pollution, and ecological risks of rare earth elements in soil of the northeastern Qinghai–Tibet Plateau. *Human and Ecological Risk Assessment: An International Journal, 25*, 1816-1831. https://doi.org/10.1080/10807039.2018.1475215

Xu, Y., Li, J., Tan, Q., Peters, A.L., & Yang, C. (2018). Global status of recycling waste solar panels: A review. *Waste Management, 75*, 450-458.

Yang, Y., Walton, A., Sheridan, R., Guth, K., Gauß, R., et al. (2017). REE recovery from end-of-life NdFeB permanent magnet scrap: A critical review. *Journal of Sustainable Metallurgy, 3*, 122–149. http://dx.doi.org/10.1007/s40831-016-0090-4

Zapf-Gottwick, R., Koch, M., Fischer, K., Schwerdt, F., Hamann, L., et al. (2015). Leaching hazardous substances out of photovoltaic modules. *International Journal of Advanced Applied Physics, 2,* 7-14. http://dx.doi.org/10.15379/2408-977X.2015.02.02.2

Zhang, D., Xu, Z., Li, C., Yang, R., Shahidehpour, M., et al. (2019). Economic and sustainability promises of wind energy considering the impacts of climate change and vulnerabilities to extreme conditions. *The Electricity Journal, 32*(6), 7-12. https://doi.org/10.1016/j.tej.2019.05.013

Zhang, H., Feng, J., Zhu, W., Liu, C., Xu, S., et al. (2000). Chronic toxicity of rare-earth elements on human beings. *Biological Trace Element Research, 73*, 1–17. https://doi.org/10.1385/BTER:73:1:1

Zhang, X., Xu, W., Wang, S., Liu, D., Deng, P., et al. (2019). Research status of recovery of tellurium from cadmium telluride photovoltaic modules. *IOP Conterence Series: Materials Science and Engineering, 782,* 022024. https://doi.org/10.1088/1757-899X/782/2/022024

Ziegler, L., Gonzalez, E., Rubert, T., Smolka, U., & Melero, J.J. (2018). Lifetime extension of onshore wind turbines: A review covering Germany, Spain, Denmark, and the UK. *Renewable and Sustainable Energy Reviews, 82*(1), 1261-1271. https://doi.org/10.1016/j.rser.2017.09.100

Address correspondence to:
Keith R. Skene
Biosphere Research Institute
5A The Den
Letham, Angus DD8 2PY
Scotland

E-mail: krskene@biosri.org